REPORT

LIGHT WEIGHT ACTIVE STRUCTURAL MATERIALS

(AOARD-10-4121)

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Introduction

This project seeks to explore the mechanical properties of light weight active structural materials. A promising example of such materials is the ferrogel system; in a ferrogel composite system, the elastic properties of a polymer matrix can be coupled with the responsive properties of a magnetic filler. This constituent property coupling results in the potential for large deformation of the entire ferrogel in an external magnetic field. These materials have been studied for a wide range of aerospace applications in which smart lightweight active structures are required, e.g., in morphing materials for UAV. Ferrogels can be deformed to high strain in three dimensions; they are lightweight and relatively inexpensive, and they can undergo cyclic deformation with minimal damage and release of byproducts into the environment. Soft polymer based actuators such as Magpol can achieve a strain of 60% and actuation stress of 184 kPa, which are higher than those of natural muscles. Magpol has been reported to respond to driving frequencies of up to 40Hz. The high strain rate, moderate driving magnetic fields combined with the other attractive performance metrics mentioned earlier show that Magpol is an excellent candidate for novel actuator applications. Ferrogels also have tunable magnetic properties, a significant advantage over bulk magnets. Therefore, understanding their mechanical behavior is crucial to optimize their performance and was investigated in this project.

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14. ABSTRACT
Magnet-polymer (Magpol) composites have very interesting soft transduction properties, including the ability to undergo large strains in response to an external magnetic field. In this project, the mechanical properties of a ferrogel composite system were investigated. The contraction behavior of composites prepared from silicone and micron sized iron particles was studied under the influence of an external magnetic field. By simply changing the boundary conditions, the actuation mode could be changed from axial contraction to a novel coiling mechanism. The actuation strain in the coiling mode is 60%, approximately 50% higher than in axial contraction. The actuation stress in coiling mode is 184 kPa, more than 10% higher than in axial contraction. Magnet-polymer composites used in the coiling mode can be useful for soft actuator applications and may be applicable for a wide range of aerospace applications in which smart lightweight active structures are required, e.g., in morphing materials for UAV.

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1. EXPERIMENTAL PROCEDURES

1.1 Synthesis of magnet-polymer composites

Spherical iron particles (ave. size 3 µm) were chosen as the filler material, polysiloxane (i.e., silicone) was selected as the polymer matrix due to its good flexibility and reasonable environmental stability.

1.2 Characterization

Sample cross-sections were prepared by cutting the samples with a sharp pen knife. The morphology of the composites was studied using a Scanning Electron Microscope (SEM). The magnetic properties were determined by a Vibrating Sample Magnetometer. The mechanical properties were tested using an Instron 5567 tensile tester. The magnetic field was generated by an electromagnet driven by a pulse power supply. The current was measured by a power analyzer.

1.3 Physical properties of Magpol

Scanning electron micrographs of silicone-iron composite samples in secondary electron mode are shown in Fig. 1. Iron particle aggregates with average size ranging from 0.1 µm to 5 µm were observed, aggregate distribution was reasonably uniform due to mixing during sample preparation.

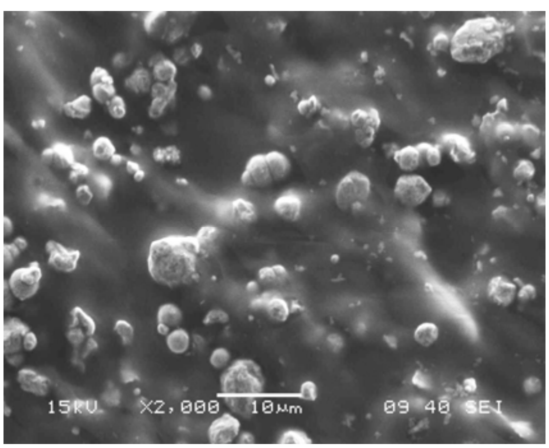


Fig.1. Physical properties of magnet-polymer composites. (a) Scanning electron micrograph of a sil-20wt%Fe sample

The room temperature magnetization curve of sil-50wt% Fe samples is shown in Fig. 2. The samples exhibited typical soft ferromagnetic properties, characterized by a non-linear magnetization curve with small hysteresis. The saturation magnetization (M_S) value of the composite increased linearly with filler concentration, suggesting that particle aggregation did not significantly affect the magnetic properties of Magpol.

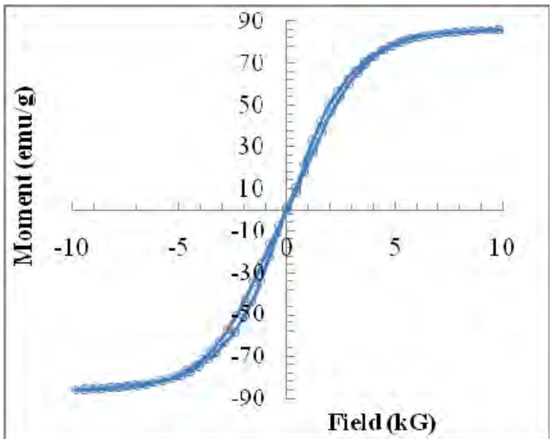


Fig. 2 Magnetic property of sil-50wt% Fe samples.

Static actuation of Magpol.

Figure 3 (a) shows the axial elongation strain of cylindrical sil-60wt%Fe Magpol samples. The path traced by points along 0-I-II-III is the sample elongation as the magnetic field (measured at the midpoint between the pole centers) was increased. The path traced by points along III-IV-V measures the relaxation as the magnetic field was decreased back to zero. A clear threshold behavior was observed. The elongation strain increased slowly with magnetic field from point 0 to point I until a threshold magnetic field was reached. When this threshold field is crossed, a large and abrupt elongation occurred (i.e., from point I to point II). The post-threshold strain was also the maximum achievable strain. Interestingly, the actuation strain of Magpol can exceed the maximum strain of natural skeletal muscle by 100 %. As the magnetic field was decreased, threshold behavior was also observed during relaxation.

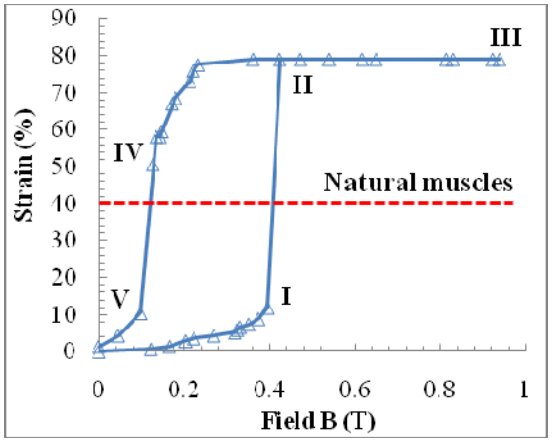
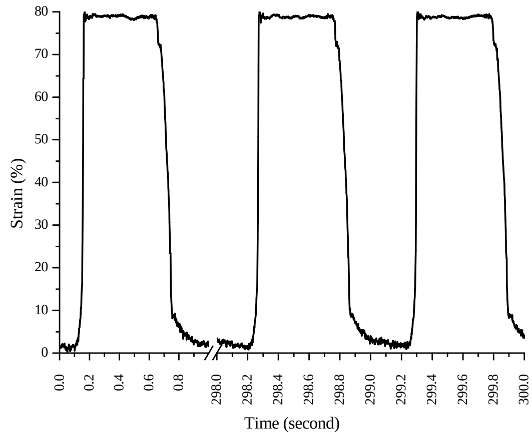


Figure 3: (a) Elongation strain as a function of magnetic field strength of a silicone-60 wt%Fe during elongation (0-III) and relaxation (III-V).

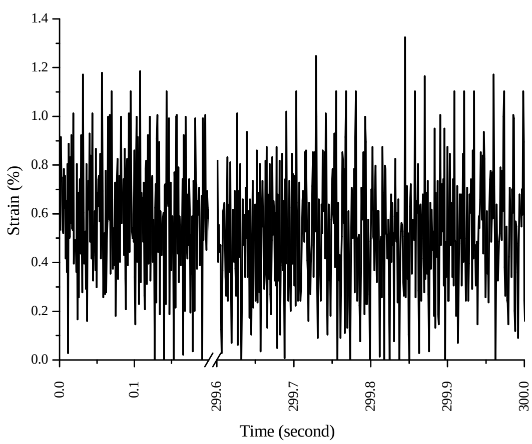
Generally, the maximum strain values of such actuators decreases with increasing actuation frequency. The frequency dependence of actuation strain of sil-60wt%Fe samples is shown in Fig. 4. At 1 Hz, 80% strain was achieved, similar to the maximum static strain. Above 1 Hz, the strain decreased sharply to 1% at 80 Hz, the highest frequency for detectable shape change.

The decrease of maximum strain with increasing frequency is commonly found in actuator systems. The frequency dependence of maximum strain, especially at low frequencies, is mainly due to slow relaxation kinetics.

In summary, the maximum actuation strain value achieved by Magpol is ~ 80%, this strain is higher than previously reported values. This is due to the lower stiffness and superior magnetic properties compared to previous studies which utilized stiffer polymers or fillers with inferior magnetic properties.



(a) 1 Hz



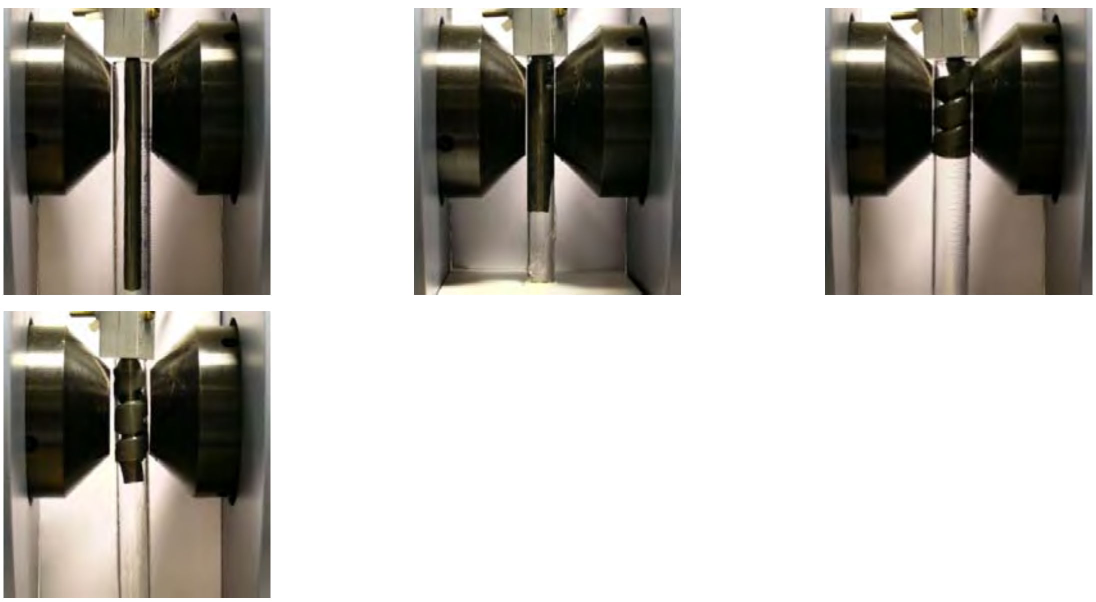
(b) 80 Hz

Figure 4: Elongation strain of sil-60wt%Fe samples as function of time at different actuation frequencies of 1 Hz and 80 Hz.

Demonstration of actuation in magnet-polymer composites by a novel coiling mechanism

Introduction

A flexible composite of polymer matrix and a magnetic filler exhibits useful and unique transduction properties when placed in an external magnetic field. Actuation occurs because an external magnetic field exerts a force on the magnetic filler particles, causing the movement of the entire composite. Shape change behavior of Magpol can be used for soft actuation, the behavior can be tuned by geometrical and material parameters to exhibit mechanical transition analogous to first or second order phase transformation, hence Magpol can be used for both linear and switching (i.e., On-Off) applications. The actuation behavior of Magpol in a compressive magnetic field was studied. Different actuation modes were achieved simply by changing the position of the sample with respect to the magnetic field or by controlling the sample deformation in the radial direction (Figure 5). A novel coiling mechanism was observed, buckling of Magpol in an external magnetic field in a suitably constrained region causes coiling. Our experimental results showed that coiling possesses higher strain and stress compared to simple axial contraction.



(a)Relaxed (b)Contracted (c) Coiled (d) Hybrid

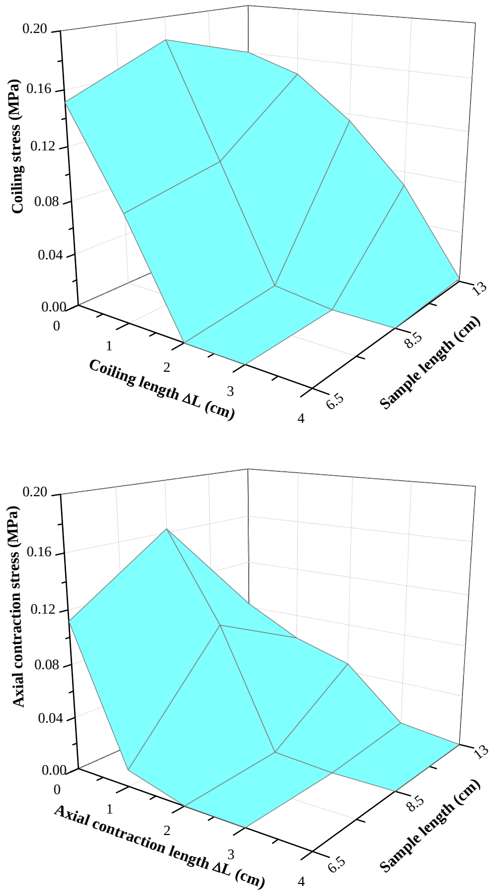
Figure 5. Actuation modes of Magpol.

The shape deformation of Magpol induced by an external magnetic field can be used for useful actuation. In general, it is known that field driven actuators like Magpol have fast switching time and better service life than ionic actuators. The coiling strain is smooth and characterized by three stages (Fig. 6). The first stage involved a small decrease in sample length, the second stage started with sample buckling, which led to coiling in the region between the coils. The coil then propagated from the region between the electromagnet poles towards the free end of the sample. The last stage was the reduction in coil height due to the attraction to the region of high magnetic field gradient (i.e., the region between the poles), this process is similar to the compression of a spring. This process continued until each ring of the coil physically touched each other.

(g) B = 0.324 T (h) B = 0.433 T (i) B = 1 T

Figure 6. The coiling behavior of silicone-20wt%(3vol%)Fe samples at different stages as observed by experiment and simulation: (a) B = 0.11T, the sample remained straight, stress builds up in the sample; (b) and (c)

The actuation stresses produced by silicone-83wt%(40vol%)Fe samples filler concentration in axial contraction and coiling modes are represented by surface graphs in Figure 7. The relationship of the actuation stress to the change in length (ΔL) and the initial sample length (L) was studied. The results revealed that the actuation stress exhibited similar behavior in both coiling and axial contraction modes. The stress values decreased as ΔL increased. The relationship of the maximum value of actuation stress with the initial sample length exhibited a peak-like behavior. This suggested that there is an optimal sample length which yields highest actuation stress.



(a) Coiling stress (b) Axial contraction stress

Figure 7. Isometric axial contraction stress and coiling stresses as a function of change in length and sample length of silicone-83wt%(40vol%)Fe samples, represented by surface graph and contour graphs.

Among the three stages of coiling process of Magpol, the second stage which involves the formation of the coil is the most important stage as it contributes more than two third of the overall strain. The actuation strain and stress produced by Magpol in coiling mode are higher than those achieved in simple axial contraction mode and previously reported values. This considerable improvement in actuation performance can enable a higher feasibility and allow a wider range of applications of actuators based on Magpol.

In this project, we wished to examine the following aspects of these materials: mechanical properties of polymer-magnet composites for light weight active structural applications, demonstration of actuation of polymer-magnet composites, Work loop method to characterize mechanical properties of polymer-magnet composites and Ashby charts of relevant property metrics of polymer-magnet composites and competing materials system.

The first two topics have been discussed above, the work loop method was initiated and relevant refs. obtained (e.g., Josephson, R.K., J. Exptl. Biology, 1985. **114**(1): p. 493 and James, R.S., Young, I.S., Cox, V.M., Goldspink, D.F., and Altringham, J.D., Pflügers Archiv European Journal of Physiology, 1996. **432**(5): p. 767-774.) and analyzed. The novelty lies in the use of concepts developed for biological actuators to soft inorganic actuators. The third and fourth topics will be completed in the next stage of the project.

In summary, magnet-polymer (Magpol) composites have very interesting soft transduction properties, including the ability to undergo large strains in response to an external magnetic field. The contraction behavior of composites of silicone and micron sized iron particles under the influence of an external magnetic field was studied. Simply by changing the boundary conditions, the actuation mode can be changed from axial contraction to a novel coiling mechanism. The actuation strain in the coiling mode is 60%, approximately 50% higher than in axial contraction. The actuation stress in coiling mode is 184 kPa, more than 10% higher than in axial contraction. Therefore, magnet-polymer composites in the coiling mode can be useful for soft actuator applications.

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